

POTENTIAL FOR NORTH AMERICAN MOSQUITOES TO TRANSMIT RIFT VALLEY FEVER VIRUS¹

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ABSTRACT. The rapid spread of West Nile viral activity across North America since its discovery in 1999 illustrates the potential for an exotic arbovirus to be introduced and widely established across North America. Rift Valley fever virus (RVFV) has been responsible for large outbreaks in Africa that have resulted in hundreds of thousands of human infections and major economic disruption due to loss of livestock and to trade restrictions. However, little is known about the potential for North American mosquitoes to transmit this virus should it be introduced into North America. Therefore, we evaluated selected mosquito species from the southeastern United States for their ability to serve as potential vectors for RVFV. Mosquitoes were fed on adult hamsters inoculated 1 day previously with RVFV. These mosquitoes were tested for infection and ability to transmit RVFV after incubation at 26°C for 7–21 days. None of the species tested (*Aedes taeniorhynchus*, *Ae. vexans*, *Culex erraticus*, *Cx. nigripalpus*, *Cx. quinquefasciatus*, and *Cx. salinarius*) were efficient vectors after they fed on hamsters with viremias ranging from 10^{4.1} to 10^{6.9} plaque-forming units (PFU)/ml. However, *Ae. taeniorhynchus*, *Ae. vexans*, and *Cx. erraticus* all developed disseminated infections after they fed on hamsters with viremias between 10^{8.5} and 10^{10.2} PFU/ml, and both *Ae. vexans* and *Cx. erraticus* transmitted RVFV by bite. These studies illustrate the need to identify the ability of individual mosquito species to transmit RVFV so that appropriate decisions can be made concerning the application of control measures during an outbreak.

KEY WORDS Rift Valley fever, vector, transmission, North America

INTRODUCTION

As illustrated by the introduction of West Nile virus into the United States in 1999 and its subsequent spread across North America, exotic arboviruses have the potential to be introduced and become established in North America and to

cause significant disease and economic disruption. Of particular concern is Rift Valley fever virus (RVFV), which has been responsible for numerous outbreaks of severe disease in ruminants and humans in sub-Saharan Africa over the past 70 years (Meegan and Bailey 1988, Gerdes 2004). Although originally limited to sub-Saharan Africa, an outbreak in Egypt in 1977 caused an estimated 200,000 human cases as well as having devastating effects on the sheep and cattle industries (Laughlin et al. 1979, Meegan 1979). The detection of RVFV on the Arabian Peninsula (Jupp et al. 2002, Shoemaker et al. 2002, Balkhy and Memish 2003, Madani et al. 2003) has raised very real concerns regarding the agricultural and medical impact this zoonotic disease agent might have if it were to continue to spread (House et al. 1992).

Although Rift Valley fever (RVF) is predominantly a problem in domestic ruminants, in which infection in pregnant animals usually results in abortion and infection of newborn animals is nearly always fatal, humans are also susceptible to infection (Easterday et al. 1962, Meegan and Bailey 1988). In humans, most infections result in an undifferentiated febrile disease and, rarely, encephalitis; however, about 1% of the infections result in hemorrhagic complications, which are often fatal. In addition, ocular sequellae can occur and cause retinal damage, including blindness (Siam et al. 1980, Al-Hazmi et al. 2005).

Rift Valley fever virus is a member of the genus *Phlebovirus*, in the family *Bunyaviridae*, and most viruses in this genus are associated with sand flies

¹ Research was conducted in compliance with the Animal Welfare Act and other federal statutes and regulations relating to animals and experiments involving animals and adheres to principles stated in the Guide for the Care and Use of Laboratory Animals, National Research Council, 1996. The facility where this research was conducted is fully accredited by the Association for Assessment and Accreditation of Laboratory Animal Care International. The views of the authors do not necessarily reflect the position of the Department of Defense or the Department of the Army.

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14. ABSTRACT The rapid spread of West Nile viral activity across North America since its discovery in 1999 illustrates the potential for an exotic arbovirus to be introduced and widely established across North America. Rift Valley fever virus (RVFV) has been responsible for large outbreaks in Africa that have resulted in hundreds of thousands of human infections and major economic disruption. However, little is known about the potential for North American mosquitoes to transmit this virus should it be introduced into North America. Therefore, we evaluated selected mosquito species from the southeastern US for their ability to serve as potential vectors for RVFV. Mosquitoes were fed on adult hamsters inoculated 1 day previously with RVFV. These mosquitoes were tested for infection and ability to transmit RVFV after incubation at 26oC for 7-21 days. None of the species tested (Aedes taeniorhynchus, Ae. vexans, Culex erraticus, Cx. nigripalpus, Cx. quinquefasciatus, and Cx. salinarius) were efficient vectors after they fed on hamsters with viremias <106.9 plaque-forming units (PFU)/ml. However, Ae. taeniorhynchus, Ae. vexans, and Cx. erraticus all developed disseminated infections after they fed on hamsters with viremias between 108.5 and 1010.2 PFU/ml, and both Ae. vexans, and Cx. erraticus transmitted RVFV by bite. These studies illustrate the need to identify the ability of individual mosquito species to transmit RVFV so that correct decisions can be made concerning the application of appropriate control measures during an outbreak.					
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Table 1. Source and colonization history of mosquitoes captured at dry-ice-baited miniature light traps from April to June 2004 and evaluated for their vector competence for Rift Valley fever virus.

Species	Location	Generation ¹
<i>Aedes vexans</i>	Indian River County, FL	P ₀ /F ₁
<i>Ae. taeniorhynchus</i>	No Name Key, FL	P ₀
<i>Culex nigripalpus</i>	Sarasota and Indian River, FL	P ₀ /F ₁
<i>Cx. (Melanoconion) erraticus</i>	Sarasota, FL, Lake Charles, LA	P ₀
<i>Cx. salinarius</i>	Lake Charles, LA	P ₀
<i>Cx. quinquefasciatus</i>	Sarasota, FL, Lake Charles, LA	P ₀ /F ₁

¹ P₀, field-collected mosquitoes; F₁, first generation progeny of field-collected mosquitoes.

in nature. Although laboratory studies indicate that various African sand flies can transmit RVFV after feeding on viremic hamsters (Turell and Perkins 1990, Dohm et al. 2000) and that South American sand flies were able to transmit RVFV after intrathoracic inoculation (Hoch et al. 1984), this virus has been associated almost exclusively with mosquitoes in nature, with the virus isolated from at least 40 species of mosquitoes in 8 genera (Meegan and Bailey 1988, Fontenille et al. 1998). Because methods of control vary for different mosquito species, it is necessary to identify which species are competent vectors and might be involved in the natural transmission cycle so that the appropriate control measures can be employed. Laboratory studies indicate that numerous species of mosquitoes are susceptible to oral infection and are able to transmit RVFV by bite (McIntosh et al. 1973b, 1980, 1983; Gargan et al. 1988, Meegan and Bailey 1988, Turell et al. 1996). However, only a limited number of mosquito species from North America have been evaluated for their potential to transmit RVFV (Gargan et al. 1988).

To determine which mosquito species might serve as potential vectors should RVFV be introduced into North America, we captured live mosquitoes in Florida and Louisiana and transported them to the United States Army Medical Research Institute of Infectious Diseases (USAMRIID), where they were evaluated for their potential to serve as natural vectors of RVFV. We selected this region as a starting point for evaluating North American mosquito species because of available mosquitoes. Rift Valley fever virus is a select agent and a Biological Safety Level (BSL)-3 agriculture facility with vaccination or a BSL-4 facility is required to work with it.

MATERIALS AND METHODS

Mosquitoes

Mosquitoes were captured in dry-ice-baited Centers for Disease Control miniature light traps (John W. Hock Co., Gainesville, FL) in Indian River County, Sarasota, and No Name Key, FL, and Lake Charles, LA, from late April through early June 2004 (Table 1). These mosquitoes were placed in screen-topped 3.8-liter cardboard con-

tainers, which were individually sealed in plastic bags. The sealed bags were added to a cardboard box before being placed in a shipping container for transport to USAMRIID. Upon arrival at USAMRIID, the mosquitoes were provided apple slices and placed in an incubator maintained at 26°C with a photoperiod of 16:8 (light:dark) h until tested for their susceptibility to RVFV.

Viruses and virus assay

The ZH501 strain of RVFV, isolated in 1977 from the blood of a 10-year-old Egyptian girl who had a fatal RVFV infection (Meagan 1979), was used throughout this study. This strain was passed twice in fetal rhesus monkey lung cells and once in Vero (African green monkey kidney) cells before use in this study.

Mosquito specimens were triturated in 1 ml of diluent (10% heat-inactivated fetal bovine serum in Medium 199 with Earle's salts [Invitrogen, Inc., Carlsbad, CA] and antibiotics) and then frozen at -70°C until tested for infectious virus by a plaque assay on Vero cell monolayers. Serial 10-fold dilutions of each specimen were tested on 6- or 12-well plates as described by Gargan et al. (1983). Viral titers were expressed as log₁₀ plaque-forming units (PFU) per specimen.

Determination of vector competence

Adult female Syrian hamsters (Harlan Sprague Dawley, Indianapolis, IN) were inoculated intraperitoneally with 0.2 ml of a suspension containing about 10⁴ PFU of RVFV to provide a source of viremic blood. These hamsters were anesthetized with a ketamine, xylazine, and acepromazine suspension 1 day after inoculation and placed individually (i.e., 1 per cage) on top of cages each containing 50–100 mosquitoes that had been deprived of a sucrose source for about 24 h. Immediately after mosquito feeding, a blood sample was collected from the anesthetized hamsters by cardiac puncture and the hamsters were then euthanized by CO₂ exposure. The blood suspensions (0.2 ml of blood added to 1.8 ml of diluent) were frozen at -70°C until assayed on Vero cell monolayers (as described above) to

determine viremias at the time of mosquito feeding. After exposure to the viremic hamsters, nonengorged mosquitoes were removed and destroyed by placing them in a freezer at -20°C . Engorged mosquitoes were provided apple slices, or a 10% sucrose solution on a gauze pledget as a carbohydrate source, and held at 26°C with a photoperiod of 16:8 (light:dark) h until tested for infection, dissemination, and transmission. Approximately 1 wk after the infectious blood meal, moist toweling or a water dish was added to each cage to stimulate oviposition. Eggs obtained from *Aedes vexans* (Meigen), *Culex nigripalpus* Theobald, and *Culex quinquefasciatus* Say were hatched and larvae reared to provide an F_1 generation that was also tested for their susceptibility to RVFV as described above.

To determine if the mosquitoes could transmit virus by bite, mosquitoes were allowed to feed on susceptible hamsters either individually or in small groups of 2–5 mosquitoes each. We considered death (or euthanasia when moribund) of these hamsters to indicate viral transmission, because RVFV infection consistently is fatal to hamsters. Nearly all RVFV-infected hamsters die or become moribund 1–3 days after virus exposure (M. Turell, unpublished data). Presence of virus was verified by isolating virus from brain tissue from a subset of the dead or euthanized hamsters (data not shown). Immediately after each transmission trial, mosquitoes were killed by freezing at -20°C for 5 min and identified to species; their feeding status was confirmed, and their legs and bodies triturated separately in 1 ml of diluent. These suspensions were then frozen at -70°C until assayed for virus.

The extent of viral infection in mosquitoes was determined by assaying a mosquito's body separately from its legs. If virus was detected in its body, but not its legs, the mosquito was considered to have a nondisseminated infection limited to its midgut. In contrast, if virus was detected in both the body and leg suspensions, the mosquito was considered to have a disseminated infection (Turell et al. 1984). Because some of the mosquitoes were tested for transmission in small pools, it was not always possible to determine which mosquito (or mosquitoes) in a pool actually transmitted virus by bite. Therefore, if more than one mosquito with a disseminated infection fed in a pool (only occurred 3 times in this study), data from that pool were not used to calculate the transmission rate, regardless of hamster survival.

The infection rate was the percentage of orally exposed mosquitoes that contained virus. The dissemination rate was the percentage of orally exposed mosquitoes (regardless of their infection status) that contained virus in their legs, and the transmission rate was the percentage of orally

exposed mosquitoes that refed (regardless of their infection status) that transmitted virus by bite. We used the extended Wald method of calculating 95% confidence intervals (Agresti and Coull 1998).

RESULTS

Hamster viremias

Viremias in the 13 hamsters used to expose mosquitoes to RVFV ranged from $10^{4.1}$ to $10^{10.2}$ PFU/ml of virus in the blood ($10^{2.6}$ to $10^{7.7}$ PFU of virus ingested per mosquito, respectively). Because these viremias represent low, moderate, and high natural viremia levels, we arbitrarily grouped the mosquitoes into those exposed to low ($10^{4.1-4.9}$ PFU/ml), moderate ($10^{6.5-6.9}$ PFU/ml), high ($10^{8.5-8.6}$ PFU/ml), or very high ($10^{10.1-10.2}$ PFU/ml) viremias.

Susceptibility to infection

For those species in which both P_0 and F_1 mosquitoes were tested, infection and dissemination rates were similar in both generations (data not shown). Therefore data for the 2 generations were combined for analysis. When exposed to viremias ranging from $10^{4.1}$ to $10^{6.9}$ PFU/ml, infection rates were low in all species tested except *Aedes taeniorhynchus* (Wiedemann) (43%; Table 2). However, when fed on hamsters with viremias $\geq 10^{8.5}$ PFU/ml, all species tested became infected, with *Ae. vexans*, *Culex erraticus* (Dyar and Knab), and *Culex salinarius* Coq. being highly susceptible with infection rates $>75\%$ and *Cx. quinquefasciatus* being only moderately susceptible with an infection rate of 26% (Table 2).

Viral dissemination

As with infection, viral dissemination rates were low when mosquitoes were exposed to a viremia $\leq 10^{6.9}$ PFU/ml, with only a single *Ae. vexans* and *Cx. nigripalpus* and 2 *Ae. taeniorhynchus* having virus detected in their legs (Table 2). However, with the exception of *Cx. quinquefasciatus*, virus was readily detected in the legs of mosquitoes that fed on hamsters with viremias $\geq 10^{8.5}$ PFU/ml.

Viral transmission

Aedes vexans and *Cx. erraticus* transmitted RVFV by bite to susceptible hamsters (Table 3). However, because so few of the other species developed a disseminated infection and subsequently fed on a hamster, we have few data about potential salivary gland barriers (Kramer et al. 1981) in these species.

Table 2. Infection and dissemination rates for mosquitoes orally exposed to Rift Valley fever virus.

Species	Days of extrinsic incubation ¹											
	7			14–17			≥19			All days combined		
	N	I.R. ²	D.R. ³	N	I.R.	D.R.	N	I.R.	D.R.	N	I.R.	D.R.
Infectious dose = 10 ^{4.1–4.6} PFU/ml												
<i>Aedes vexans</i>				10	10	0	2	50	50	12	17 (3.5–46.0)	8 (0.1–37.5)
<i>Culex quinquefasciatus</i>							40	3	0	40	3 (0.1–14.0)	0 (0.0–10.4)
<i>Cx. nigripalpus</i>				10	0	0	72	4	0	82	4 (0.1–10.7)	0 (0.0–5.4)
<i>Cx. salinarius</i>	10	20	0	3	0	0	18	0	0	31	6 (0.8–21.8)	0 (0.0–13.1)
Infectious dose = 10 ^{6.5–6.9} PFU/ml												
<i>Cx. (Melanoconion) erraticus</i>				19	5	0	18	11	0	37	8 (2.1–22.0)	0 (0.0–11.2)
<i>Cx. salinarius</i>				10	0	0	7	0	0	17	0 (0.0–21.6)	0 (0.0–21.6)
<i>Cx. nigripalpus</i>				10	20	10	10	10	0	20	15 (4.4–36.9)	5 (0.1–25.4)
<i>Ae. taeniorhynchus</i>	10	50	10	4	25	25				14	43 (21.3–67.5)	14 (2.8–41.2)
Infectious dose = 10 ^{8.5–8.6} PFU/ml												
<i>Ae. vexans</i>				10	80	30				10	80 (47.9–95.4)	30 (10.3–60.8)
<i>Cx. quinquefasciatus</i>				73	26	0				73	26 (17.3–37.2)	0 (0.0–6.0)
Infectious dose = 10 ^{10.1–10.2} PFU/ml												
<i>Ae. vexans</i>				15	93	73	17	100	82	32	97 (82.9–99.9)	78 (61.0–91.6)
<i>Cx. (Mel.) erraticus</i>				14	79	64				14	79 (51.7–93.2)	64 (38.6–83.8)
<i>Cx. salinarius</i>				8	88	38				8	88 (50.8–99.9)	38 (13.5–69.6)

¹ N, number tested; I.R., infection rate; D.R., dissemination rate.² I.R. = percentage of mosquitoes containing virus in their bodies.³ D.R. = percentage of mosquitoes, regardless of their infection status, containing virus in their legs.

DISCUSSION

Despite both the medical and economic risk that RVFV poses to North America, there have been few studies on the potential for North American mosquitoes to transmit RVFV (Gargan et al. 1988; Turell et al. 1985, 1988). This is the first study to evaluate field-collected mosquitoes from the southeastern United States for their ability to transmit this virus. Both *Ae. vexans* and *Cx. erraticus* readily developed disseminated viral infections and transmitted RVFV by bite after

oral exposure to relatively high viremias ($\geq 10^{8.5}$ /ml of blood). In addition, although *Ae. taeniorhynchus* was not tested at the higher viremia levels, it was the most susceptible species tested when fed on hamsters with viremias ranging from $10^{6.5}$ to $10^{6.9}$ PFU/ml, and based on studies with colonized *Ae. taeniorhynchus*, this species is a relatively efficient vector of RVFV (Turell et al. 1985). Although the only *Ae. taeniorhynchus* with a disseminated infection that fed on a susceptible hamster in the present study did not transmit virus by bite, previous studies with both field-

Table 3. Transmission of Rift Valley fever virus by mosquitoes captured in the southeastern United States that had been exposed to virus by feeding on viremic hamsters.

Species	Viremia	Transmission Rate ¹	Transmission (D) rate ²
<i>Aedes taeniorhynchus</i>	$10^{6.5-6.9}$	0/4 (0%)	0/1 (0%)
<i>Ae. vexans</i>	$10^{8.5-8.6}$	1/4 (25%)	1/1 (100%)
<i>Ae. vexans</i>	$10^{10.1-10.2}$	3/13 (23%)	3/9 (33%)
<i>Culex (Melanoconion) erraticus</i>	$10^{6.5-6.9}$	0/11 (0%)	NT ³
<i>Cx. (Mel.) erraticus</i>	$10^{10.1-10.2}$	2/6 (33%)	2/4 (50%)
<i>Cx. nigripalpus</i>	$10^{4.1-4.9}$	0/5 (0%)	0/1 (0%)
<i>Cx. quinquefasciatus</i>	$10^{4.1-4.9}$	0/29 (0%)	NT
<i>Cx. quinquefasciatus</i>	$10^{8.5-8.6}$	0/13 (0%)	NT
<i>Cx. salinarius</i>	$10^{4.1-4.9}$	0/7 (0%)	NT
<i>Cx. salinarius</i>	$10^{6.5-6.9}$	0/13 (0%)	NT
<i>Cx. salinarius</i>	$10^{10.1-10.2}$	0/2 (0%)	NT

¹ Number of mosquitoes transmitting virus/number of virus-exposed mosquitoes that refed (percentage transmitting).² Number of mosquitoes transmitting virus/number of mosquitoes with a disseminated infection that refed (percentage transmitting).³ NT, not tested.

collected and colonized *Ae. taeniorhynchus* indicate that this species has a moderate salivary gland barrier and about 50% of this species with a disseminated infection would transmit RVFV by bite (Turell et al. 1985, Turell and Bailey 1987, Gargan et al. 1988). The infection and dissemination rates observed for *Ae. taeniorhynchus*, *Ae. vexans*, and *Cx. erraticus* are consistent with those reported for African vectors of RVFV (Jupp and Cornel 1988, Turell et al. 1996, 2007, 2008). Therefore, these species should be considered as potential vectors of RVFV should this virus be introduced into areas where these species are found.

The *Culex* (*Culex*) species tested were relatively incompetent vectors of RVFV, with only a single *Cx. nigripalpus* that fed on a hamster with a viremia of $10^{6.9}$ PFU/ml and none of 73 *Cx. quinquefasciatus* that fed on a hamster with a viremia of $10^{8.5}$ PFU/ml developing a disseminated infection. In contrast, several African members of this subgenus are relatively efficient vectors of RVFV, including *Culex pipiens* L., *Culex zombiensis* Theobald, *Culex perexiguus* Theobald, *Culex antennatus* (Becker), *Culex tritaeniorhynchus* Giles, and *Culex poicilipes* (Theobald) (Gad et al. 1987, 1989; Jupp and Cornel 1988, Jupp et al. 2002, Meegan et al. 1980, Turell et al. 1996, 2007), with reported infection rates ranging from 60% to 95%. The apparent inability of *Cx. quinquefasciatus* to transmit RVFV in this study is similar to the results of a recent study in which *Cx. quinquefasciatus* captured in Kenya failed to transmit virus by bite despite feeding on hamsters with viremias ranging from $10^{9.7}$ to $10^{10.3}$ PFU/ml (Turell et al. 2007). This is surprising because of the close relationship between this species and *Cx. pipiens*, the incriminated vector during the outbreak in Egypt in 1977–79 (Meegan et al. 1980). Is the poor vector competence of North American *Cx. quinquefasciatus* due to a difference in vector competence between *Cx. pipiens* and *Cx. quinquefasciatus*, or is it a difference between North African and North American members of these species? This illustrates the need to identify which mosquito species found to be infected in nature are actually able to transmit that virus by bite. Once a species has been confirmed as a vector, appropriate control measures can be implemented to reduce the number of those mosquitoes, especially during an outbreak.

Although most of the *Culex* (*Culex*) species tested in this study were inefficient vectors of RVFV, *Cx. salinarius* was susceptible when fed on a hamster with a viremia of about $10^{10.1}$ PFU/ml, and its viral infection and dissemination rates were similar to those reported by Gargan et al. (1988) for this species. We were unable to determine if *Cx. salinarius* had a salivary gland barrier because none of the *Cx. salinarius* with a disseminated infection took a second blood meal.

However, nearly half of those with a disseminated infection transmitted RVFV by bite when fed on a susceptible hamster in an earlier study (Gargan et al. 1988). The only species of *Culex* (*Melanoconion*) tested, *Cx. (Mel.) erraticus*, was a moderately efficient vector, with vector competence similar to that of *Ae. vexans*. This is the first member of this subgenus to be evaluated for its ability to transmit RVFV, and its relative efficiency as a vector indicates that other members of this subgenus should be evaluated.

The viremias used in this study, $10^{4.1-10.2}$ PFU/ml, are consistent with viremias determined for natural infections with RVFV, where viremias in lambs and calves were as high as $10^{10.2}$ and $10^{9.2}$ mouse intracranial 50% lethal dose, respectively (McIntosh et al. 1973a). Therefore, the results obtained in our study should apply to the various mosquito species tested, should they feed on RVFV-infected cattle or sheep in a natural outbreak of RVF. Because this study focused on mosquitoes from the southeastern United States and mosquito populations vary in their ability to transmit viruses, the results of the present study may not apply to populations from other regions in North America. Additional studies are required to evaluate other potential vectors of RVFV in North America and to determine the role of other factors (e.g., environmental temperature) on the transmission of this pathogen.

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